Topographic Influence on Internal Waves and Mesoscale Oceanic Dynamics

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LONG TERM GOAL

The long-term goal of our research is to identify and quantify key processes responsible for topographically induced oceanic mixing and to evaluate basin-averaged turbulent diffusivities akin to such processes.

OBJECTIVES

The current project deals with (i) the decay of tidal internal-wave energy downstream of submarine ridges in deep ocean, and (ii) internal-wave induced fluxes in the coastal zone. The work includes processing of observational data as well as numerical and theoretical analyses. Creating an extensive database on a CD-ROM containing the mooring and profiling measurements taken by Russian oceanographers in the regions of uneven topography will substantially enhance data resources available for the western oceanographic community.

APPROACH

The work involves collaboration with a group of prominent oceanographers of the Former Soviet Union who have collected extensive sets of data on microstructure, fine-structure and internal waves on ocean shelves, near submarine ridges and seamounts in Atlantic, Pacific, Indian and Arctic oceans. A close working relationship has been established with Dr. Eugene Morozov pertinent to the studies of tidal internal waves near submarine ridges and on creating a mooring database. Drs. S. Shapovalov and A. Ksenofontov collaborate in numerical efforts on modeling of the near-bottom turbulence affected by tidal flows. The efforts of Drs. G. Shapiro and V. Navrotsky are focused on the modeling of internal wave-induced fluxes in shallow coastal waters and on the analysis of the modification of internal waves as they propagate off from deep-ocean topographies. During the past year our research team analyzed field data obtained from the western Indian Ocean, east of the Mascarene Ridge in the Pechora Sea (a shallow wide bay of the Barents Sea), shelf zones south of Taiwan and from the Japan Sea. The measurements were carried out using the mooring current meters POTOK [Fomin, et al. 1989], Neil Brown CTD profiler and double line thermistors [Shapiro and Serebryany 1999].

WORK COMPLETED

A preliminary version of the mooring database of the P.P. Shirshov Institute of Oceanology has been created. The basic information on data files is arranged in table format. An example is shown below. North Atlantic, South of Iceland.

Filename	Buoy number	Measurements start on	Sampling interval	Duration	Latitude	Longitude	Instrument depth	Seafloor depth	Parameters
isl--1-1.dat	1	17.08.1989 00-00	60 min	77 h	54 09 N	26 44 W	1000	3366	U V T
isl--1-2.dat	1	17.08.1989 00-00	60 min	317 h	54 09 N	26 44 W	1500	3366	U V T

The data files are in the ASCII format. Each file contains time series of current components *U* and *V* and temperature *T* along with supplementary information in the WOCE standard. The data files can be easy opened or downloaded from an external source. A search system, which is in the HTML format, allows access to the information via any web browser. The data are sorted by the name of the experiment, region and year. The database and a search system are currently on a CD-ROM and will be publicly available. The database will be soon placed on an ASU computer server and will be linked to the EFD web page *http://www.eas.asu.edu/~pefdhome*. The CTD data of several expeditions in the South China Sea, Japan Sea and Bering Sea have been retrieved from the archives of the Pacific Oceanological Institute (Vladivostok) and examined for the data quality assurance and are being prepared to be transferred to the web site.

We completed a study on the spatial variations of the amplitude of tidal internal-waves generated in the main pycnocline of the Indian Ocean by the Mascarene Ridge. The decay of the wave amplitudes was approximated by an analytical formula.

A new version of the diagnostic/data assimilation model was developed to calculate residual mass transports induced by non-linear internal waves. It utilises CTD and double-line thermistor data to initialise numerical calculations. The model was tested for shallow Pechora Sea of the Russian Arctic.

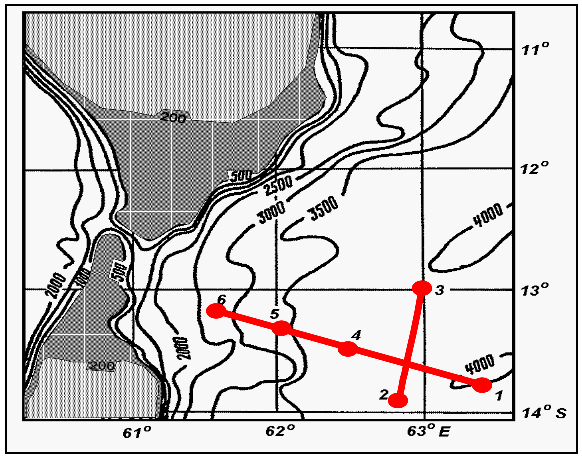
We extended our model of the generation of thermohaline fine structure in sharp near-surface thermoclines [FY98 ONR 32-Year End Report] to predict the benthic boundary layer influenced by tidal flows. A number of numerical experiments have been carried out with this modified model.

RESULTS

A. ***Tidal internal wave propagation over large distances in the Indian Ocean***

The objective of the study was to estimate the distance of propagation and decay of strong internal tides generated at the Mascarene submarine ridge. The measurements were taken in 1987 and in 1995-1997. In 1987 a cluster of 6 buoys was set east of the Mascarene Ridge with measurements of currents and temperature at 100, 200, 300, 500, 700, 1000, 1200, 1800 and 2500 m (Fig. 1) over a two-week period.

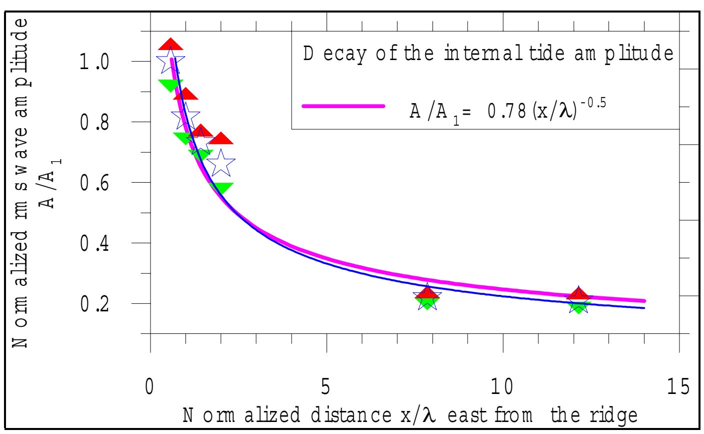
The largest amplitudes of semidiurnal internal oscillations were registered in the main thermocline between 1000 and 1200 m, with a maximum height of A_{max} = 80 m. Averaging over the total period of measurements yielded a rms estimate for A equal to 58 m with 10% bootstrap confident limit of 53 - 61 meters. Considering the buoy cluster as an antenna for tidal internal waves, the space-time dependent spectra at the semidiurnal frequency were calculated (not shown here for brevity). It was found that a tidal internal wave having the wavelength λ of 140-150 km propagates from the Mascarene Ridge in the southeast (azimuth is equal to 110°). Due to the lack of measurements on the West Side of the ridge, waves propagating in that direction could not be identified. Assuming that tidal internal waves are quasi-stationary relatively to the spring/neap variability of barotropic tide, it is possible to use the data obtained in different years to analyze the decay of wave amplitudes over a long distance from the ridge.



1. The location of the mooring array east of the Mascarene Ridge (1987 experiment) in a background of bathymetric contours (meters). Depths of the ocean floor < 500 m colored in green, z < 200 m is shown in brown.

Therefore, we supplemented the measurements taken in 1987 with those taken in 1995-1997 at two mooring stations in the central Indian Ocean (15°S, 72°E and 15°S, 77°E). The temperature fluctuations at these moorings were recorded during 6 months of each year at the depth of 1200 m. The temperature records at moored buoys were converted into vertical displacements using the mean vertical temperature gradient calculated from the CDT profiles. The normalized values of rms amplitudes of tidal internal waves A/A_{max} for moorings 1,4,5 and 6 along with averaged estimates for two far stations are shown in Figure 2 as a function of the normalized distance x/λ. The decay of wave amplitudes can be approximated by a power law. The result of the best least-square fitting is shown in Figure 2 by a thin line. The heavy line is the overall dependence

$$\widetilde{A}(\widetilde{x}) = 0.87 \times \widetilde{x}^{-0.5},$$



2. The decay of the normalized rms amplitude of semidiurnal tidal internal waves (stars) as a function of the distance east of the Mascarene Ridge. The horizontal axis is normalized by the average wavelength = 140 km at a depth of 1200 m. The triangles show the upper (red) and lower (green) 10% bootstrap confident limits.

where $\widetilde{A}$ and $\widetilde{x}$ are the normalized wave amplitude and distance from the ridge. It is clear that the amplitude of tidal waves decreases by 10% over one wavelength. The results also indicate that strong semidiurnal internal tides generated near a submarine ridge loose about 80% of their potential energy, which is proportional to the squared displacement amplitude, at a distance of about three wavelengths. Then the wave amplitudes continue to decrease gradually to a background level of about $0.2A_{\max}$.

Further investigations on the energetics and dynamics of tidal internal waves continue in collaboration with Dr. Eugene Morozov. One of the quantities of interest is the variation of the depth averaged (over a range ΔH) energy $E_{TIW} = 0.25\rho_o\left(u_{TIW}^2 + v_{TIW}^2 + w_{TIW}^2 + N^2A^2\right)\Delta H$ with the distance from the topography, its conversion to irreversible small-scale mixing and global consequences therein.

B. ***Internal waves and fine structure in coastal zones***

1. *The influence of non-linear internal waves on cross-shelf fluxes*

This part of the project dealt with the influence of internal waves on the generation of residual transports in shallow coastal regions far from potential internal-wave sources. A case study of the water fluxes induced by non-linear internal waves was carried out using the data obtained from the shallow Pechora Sea of the Arctic Ocean (69-70 N, 59-60 E). Dr. Shapiro analysed field measurements, developed numerical model, and performed numerical experiments in this regard.

Field measurements were carried out in the Pechora Sea during August - September of 1998 as a part of the 13th expedition of R/V AKADEMIK SERGEY VAVILOV of the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences. A Neil Brown Mark-III profiler and double-line thermistors of 10 and 20 meters length (sampling interval ranges from 0.1 to 4 sec) were deployed from an anchored ship, and the time variation of the absolute depth of the thermocline was monitored at several locations. These data were used as initial conditions for numerical experiments.

The stratification above and below a narrow thermocline in shallow waters of the Pechora Sea (the bottom depth does not exceed 20 m) was very weak. Therefore, a two-layer internal wave theory was used for modelling horizontal fluxes. The intermittency factor for high frequency waves (the percentage of time where the wave amplitude exceeds 1 m, which can be construed as a relatively high wave with respect to the average thickness of the near-bottom layer of 5-10m) was about 30%. At times, solibores or packets of soliton-like waves were also observed. Well-developed (often high-frequency) internal waves were detected as far as 1000 km away from the shelf break. The highest value of the non-linearity parameter, i.e. the ratio of the wave amplitude to the effective water depth, $H_{eff} = (H_1 \times H_2)/(H_1 + H_2)$, was found to be 0.32; here H_1 and H_2 are the thickness of the upper and lower layers, respectively. The high level of non-linearity, estimated from the observations, supports the notion that internal waves may noticeably enhance the pumping of water and the transport of dissolved matter across the shelf as a result of the Stoke's drift.

The mass flux produced by non-linear IW was calculated using the model of Inall et al. [1997]; one of the advantage of this model is that it does not require the internal waves to be periodic. The model was used to estimate the actual and time averaged (residual) mass fluxes in the bottom boundary layer. On the contrary to the Stoke's theory, the non-linear component of orbital velocity contributed only little to the net (time-averaged) flux according to our calculations. Numerical experiment showed that the major contribution to the horizontal mass flux comes from the asymmetry of the shape of the thermocline. In turn, non-linear processes that act for an extended period of wave evolution before the wave reaches the measurement site located in shallow water contributed to the mass flux. The above results should be regarded as preliminary and require further careful analysis.

2. *Modification of internal waves in the coastal zone of western Pacific.*

The analysis of internal-wave propagation in the Japan Sea revealed a significant change in the wave spectra when thermocline descends to the bottom. Internal waves with a wavelength on the order 1000 m almost disappeared, but shorter waves with wavelengths 200-300 m became significantly more energetic than in deep water. Dr. V. Navrotsky found that in the South China, Japan and Bering Seas, the low-frequency waves become considerably shorter as they propagate from deep waters to the shore, *viz.* the phase velocity of waves decreases in shallow waters. The same was true for group velocities. High-frequency waves, however, did not show such behavior, but they dependent on the variability of mean currents than their low-frequency counterparts. The resonant interactions between internal wave modes were more frequent and distinct in shallow waters as a result of the concentration of energy into thin layers.

IMPACT/APPLICATION

The mooring database which is being developed under the current project distributes valuable information and measurements of currents in various regions of Atlantic, Pacific and Indian Oceans. Through this project, the international oceanographic community will have access to extensive data sets obtained by oceanographers of the Former Soviet Union, and these data can be used for gaining deeper insights into mesoscale and internal wave dynamics of oceans. The data can be used in the context of numerical simulations, to verify or improve models.

The method of calculating horizontal mass flux induced by non-linear internal waves in shallow waters is a useful tool for evaluating the role of internal wave on the transport of sediments and other species in coastal regions.

TRANSITIONS

At this time, no direct transitions were realized with operational personnel of the Navy. The data sets that are being compiled, however, is expected to be of immense utility in developing and validating operational numerical models.

RELATED PROJECTS

The P.I. has established close collaboration with oceanographers from the Former Soviet Union (Drs. Shapovalov, Morozov, Shapiro, Navrotsky, Ksenofontov) who are actively participating in the project. The PIs' were awarded a COBASE travel grant by the US National Research Council to initiate long-term collaborative with Dr. Morozov with regard to the work on topographically induced oceanic mixing.

The P.I. maintains contacts with Dr. Don Delisi of NWRA (Bellevue, WA) as a part of an ongoing project dealing with the testing of Russian-build EM velocity sensor. Field tests on this sensor are scheduled for year 2000.

The Co-P.I. is involved in an ONR funded project entitled "Dynamics of Cobbles Under the Action of Waves and Mean Currents" which deals with laboratory investigations on coastal waves and their breaking.

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